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AIR-COUPLED CMUT ARRAYS BASED ON MUMPS

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ABSTRACT
Manufacturing capacitive micromachined ultrasonic transducers (cMUTs) is possible using several low cost standard processes. The multi-user MEMS process (MUMPS) offers this possibility. However, it has some limitations: diaphragms and air gaps of approximately 2 µm thick limit the performance of the resulting device.

With the aim of developing an air-coupled 2-D array, several typologies were designed, made and characterized. It was shown that all of them work as was expected with a good bandwidth in air but there were some negative effects on their behaviour. The polysilicon layers are heavily doped and in principle they do not need a metallization layer. Nevertheless studying the obtained results it was shown that when a metal electrode is deposited over the polysilicon membrane, the performance of the transducer is improved. Moreover, the acoustic pressure leaving from the etch holes and other acoustical ports added in several designs have a negative effect in the emitted pressure. In this work, square shaped polysilicon membranes with a gold electrode have been simulated and made to reduce these detected negative effects. Two different array apertures, a 1-D array and a sparse 2-D array, have been designed to study their efficiency.

I INTRODUCTION
Capacitive micromachined ultrasonic transducers (cMUTs) have a wide range of applications such as medical imaging and non destructive evaluations (NDE) among many others. A cMUT cell basically consists of a fixed electrode and a flexible membrane that supports a second electrode [1-2]. Because of its high efficiency and bandwidth in liquids, medical imaging and other immersion applications are the most established applications of this technology. Due to its small dimensions it is possible to built complex array apertures. Nevertheless the need of using custom manufacture processes makes expensive the fabrication of these transducers. This work shows the design steps of a 1-D array and a sparse 2-D array using the low cost standard process MUMPS. This process uses heavily doped silicon, heavily doped polysilicon layers as the structural material, gold for electrical routing, deposited oxide as the sacrificial material and silicon nitride for electrical isolation.

In a previous work [3] it was presented five typologies of cMUT devices which use different combinations of MUMPS process layers. Some of them use the polysilicon membrane as the top electrode taking advantage of its electrical properties. As the polysilicon is heavily doped with phosphorus, it can be assumed as a conductor. Moreover, due to the standard dimensions of the layers (approximately 2 µm) it was though to change the boundary conditions of some membranes to improve the efficiency of the transducer. Several square membrane designs are clamped as its sides while other diaphragms have two opposite sides free (a bridge configuration). It was demonstrated in [4] that the air leaving from the acoustical ports (free sides of the membrane and etch holes in the membrane) has a negative effect in the total pressure. They radiate in counterphase with the pressure from the membrane. Moreover, with the addition of a metal electrode it was shown that the average displacement of the membrane increases with respect to the same design without metallization. Because of these results, the design presented in this work uses clamped boundary conditions and a gold electrode to improve the performance of the transducer.

II DEVICE FABRICATION

Fig. 1 shows the fabrication process to manufacture the single cMUT cell. The first step is to cover the heavily doped silicon wafer with a 0.6 µm thick LPCVD silicon nitride isolation layer. Then it is deposited the first oxide and the second sacrificial layer where is used the ANCHOR2 mask that is patterned and etched by RIE. This step provides anchor holes that are filled with the polysilicon layer POLY2 obtaining the membrane of the transducer. The 0.5 µm thick gold layer is finally deposited to obtain the top electrode of the cell. Finally the etch holes are included in the membrane and metal layers to provide the oxide release obtaining the resulting device. It basically consists of the silicon wafer as the bottom electrode, the polysilicon as the membrane and the gold as the top electrode. Fig. 2 shows a photograph of two elements of the lineal array where it is shown in detail one membrane, its metal electrode and the etch holes.

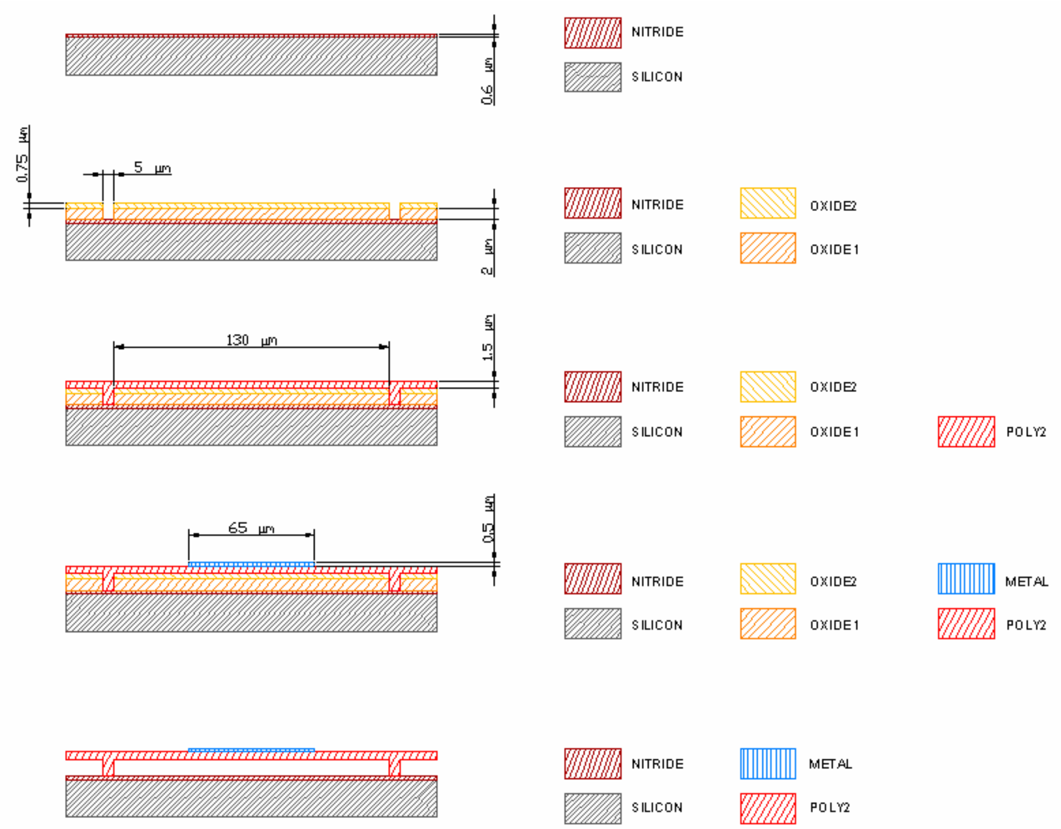

Figure 1 – Fabrication process flow for the single cMUT cell.

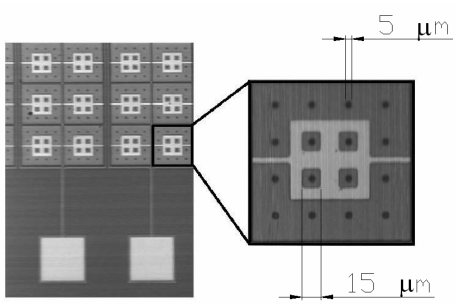

Figure 2 – cMUT cell membrane, metal electrode and etch holes.

III ARRAY DESIGN

Two different arrays were designed to study the possibilities of designing different apertures using the MUMPS process: a lineal array with 33 elements with 68×2 cells electrically connected in parallel and a sparse array with 244 elements with 3×3 cells.

Using the commercial package ANSYS the resonant frequency of the single cell was simulated. The central frequency is located around 720 kHz. It results in a wavelength of approximately 470 µm. These characteristics and the die size (design surface) in the MUMPS process will limit the design possibilities of the whole transducer. As the membrane size is around λ/3 and the die size is 1×1 cm, the number of elements in the array, the element size and so the number of cells in an element must be adjusted to these limits trying to lose the less possible efficiency.

III.1 Lineal Array

Using the cMUT cells described in the previous paragraphs, a lineal array was made. The 1-D array element consists of 68×2 cells electrically connected in parallel. This is the higher quantity of cells that is possible to use because of the die size. The width of the element is defined by the wavelength of the transducer. It was shown that λ has a value of around 470 µm, so to avoid grating lobe formation a separation between elements of approximately λ/2 should be used. Using this technology, this separation corresponds with the use of two membranes per element width. A maximum of 33 elements is obtained adjusting to the die size.

The array prototype is shown in Fig. 3.

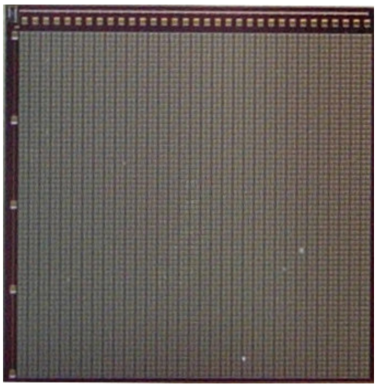

Figure 3 – Lineal array prototype.

III.2 Sparse Array

This section consists of a brief description of the 2-D sparse array made using cMUTs based on MUMPS and the basic steps followed to its fabrication. The detailed design steps of this array are described in [5].

To obtain the 2-D sparse array the following specifications were taken into account:

- Main lobe with a resolution range from 1 to 1.5 degrees. This yields in an array size of 40 times the wavelength which implies 6400 elements in a common 2-D array.
- To reduce the electronics and design complexity (because of the difficult interconnection to pads), it was though to use a random sparse array design reducing the number of active elements.
- To avoid grating lobe formation, the array element should have a size of λ/2.

In a previous paragraph it was shown that the die surface influences in the array size. The die is limited to 1×1 cm, that is 20 times the wavelength. The first array specification indicates that the array should have a size of 40λ. To solve this inconvenience it was proposed to divide the design in four quadrants to be assembled in the manufacture process. To reduce the fabrication cost, only one quadrant was designed taking advantage of the circular symmetry as it is shown in Fig. 4. In principle these symmetries are objections for these array designs. One of the basis of designing 2-D sparse arrays is to avoid these symmetries but for this case this loss can be assumed. Using this sparse aperture the second specification is also carried out.

The third specification of the design indicates that the array element should have a size of λ/2. Using this cMUT technology, the element is limited to the use of one membrane per element to obtain approximately this size. This is insufficient to obtain an efficient element, so to increase the active surface of the array the element is enlarged up to λ. This means array elements of 3×3 cMUT cells electrically connected in parallel.

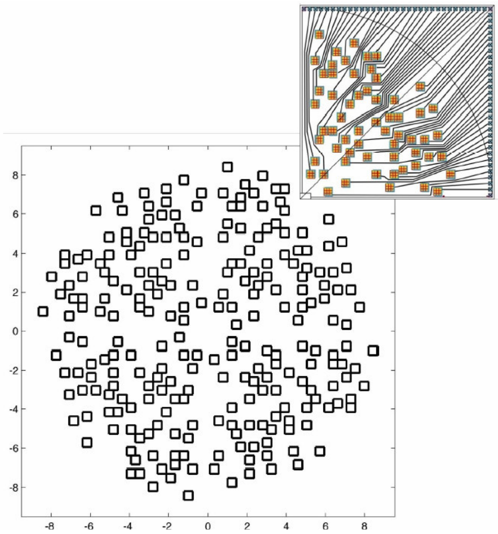

Figure 4 – 2-D sparse array design.

Following these design rules, a sparse array with 244 elements was designed and made. It presents a dynamic range for a narrow band signal of around 23 dB for a transmission-reception calculation based in its array factor. For a wide band signal, the impulse response presents a dynamic range of 40 dB. Fig. 5 shows this last calculation.

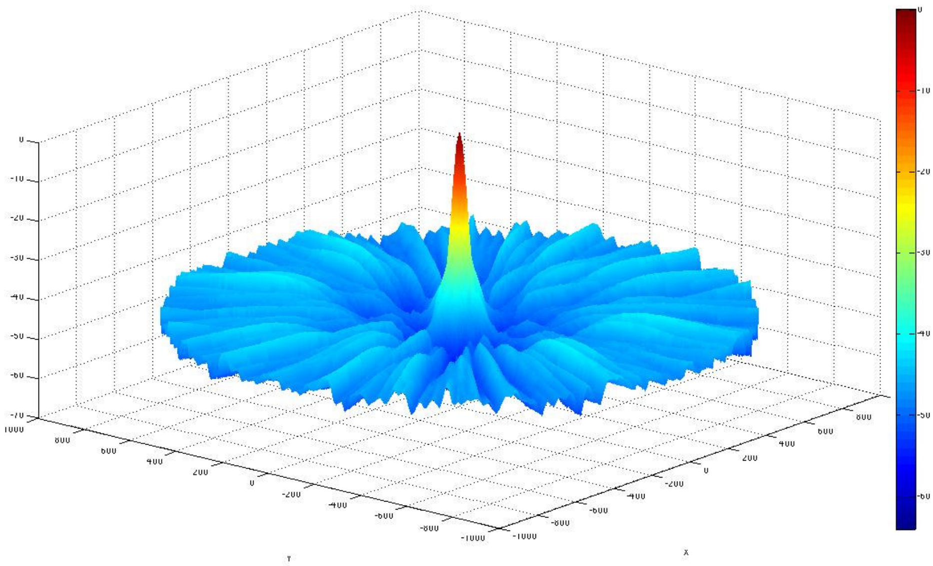

Figure 5 – Wide band array factor for the sparse array.

Fig. 6 shows the developed prototype after the assembly of the design.

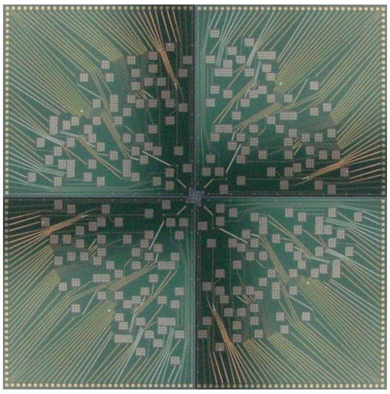

Figure 6 – 2-D sparse array prototype.

CONCLUSIONS

A 1-D lineal array and a 2-D sparse array were designed using cMUTs based on the MUMPs fabrication process. The single cMUT cell uses a silicon (bottom electrode) – gold (top electrode) configuration with a heavily doped polysilicon membrane. This design pretends to improve past cMUTs designs based on MUMPS. Several array design problems due to restrictions of the MUMPS technology were overcome affecting the less possible the performance of the device. At the moment all the array prototypes are under testing.

AKNOWLEDGEMENTS

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